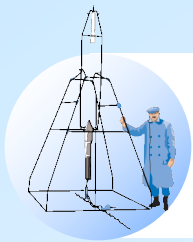


Micro- and Nano-Scale Electrically Driven Two-Phase Thermal Management

Jeffrey R. Didion
Senior Thermal Engineer
Manager, Nanotechnology Facility

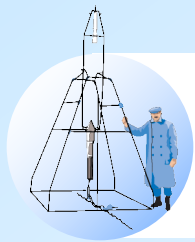




Technical Overview

- **Fundamental Research:**
 - *Electrically Driven Liquid Film Boiling* NASA HQ SLPSRA Division NNX12AR32G (Yagoobi/WPI & Didion)
 - *Self-Sensing Thermal Management Using nano-enhanced Polymers* NSTRF FY13 (Bruck & Sauerbrunn/UMD & Didion)
 - *Study of Micro/Nano Scale EHD-Driven Flow Distribution Control and Heat Transfer Enhancement for Thermal Control Systems* NSTRF FY14 (Talmor & Yagoobi/WPI & Didion- NSTRF Mentor)
- **Flight Hardware: Electrically Driven Liquid Film Boiling**
 - ISS Fluids Rack – FY21





EHD Thin Film Boiling Experiment: Electrophoretic – Conduction Pumping

Objective:

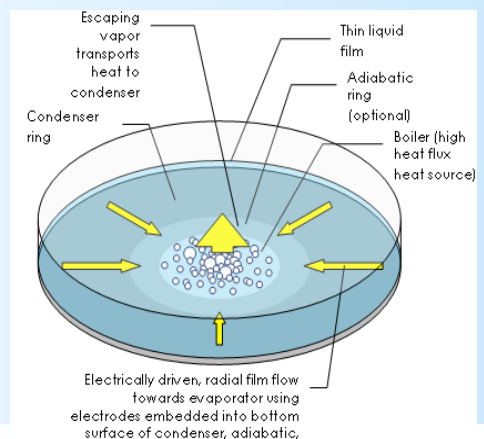
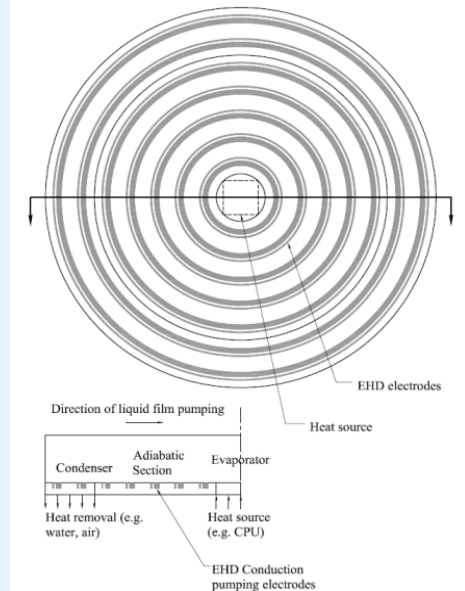
- ♦ Characterize the effects of gravity on the interaction of electric and flow fields in the presence of phase change specifically pertaining to:
 - The effects of microgravity on the electrically generated two-phase flow.
 - The effects of microgravity on electrically driven liquid film boiling (includes extreme heat fluxes).
- ♦ Electro-wetting of the boiling section will repel the bubbles away from the heated surface in microgravity environment.

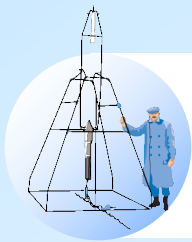
Relevance/Impact:

- ♦ Provides phenomenological foundation for the development of electric field based two-phase thermal management systems leveraging EHD, permitting optimization of heat transfer surface area to volume ratios as well as achievement of high heat transfer coefficients thus resulting in system mass and volume savings.
- ♦ EHD replaces buoyancy or flow driven bubble removal from heated surface.

Development Approach:

- ♦ Conduct preliminary experiments in low gravity and ground-based facilities to refine technique and obtain preliminary data for model development.
- ♦ ISS environment required to characterize electro-wetting effect on nucleate boiling and CHF in the absence of gravity.
- ♦ Will operate in the FIR – designed for autonomous operation.



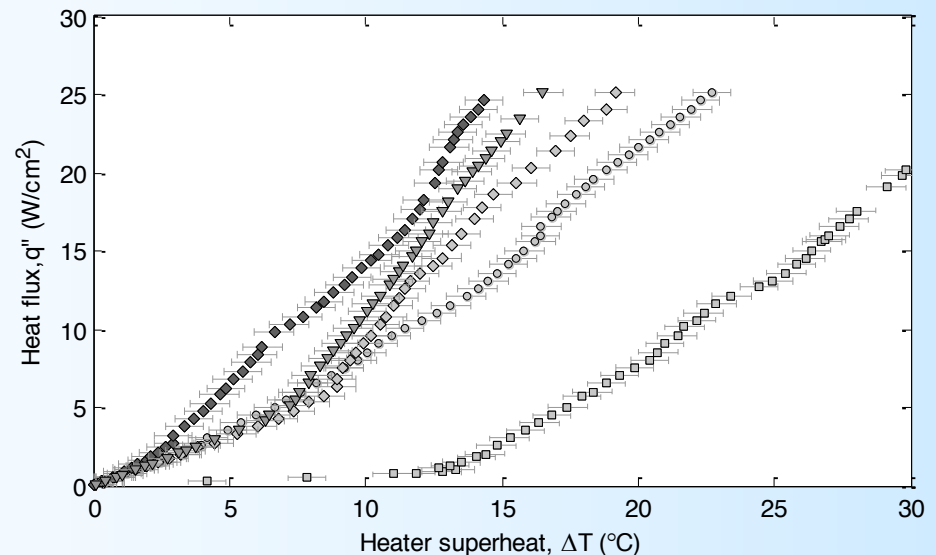
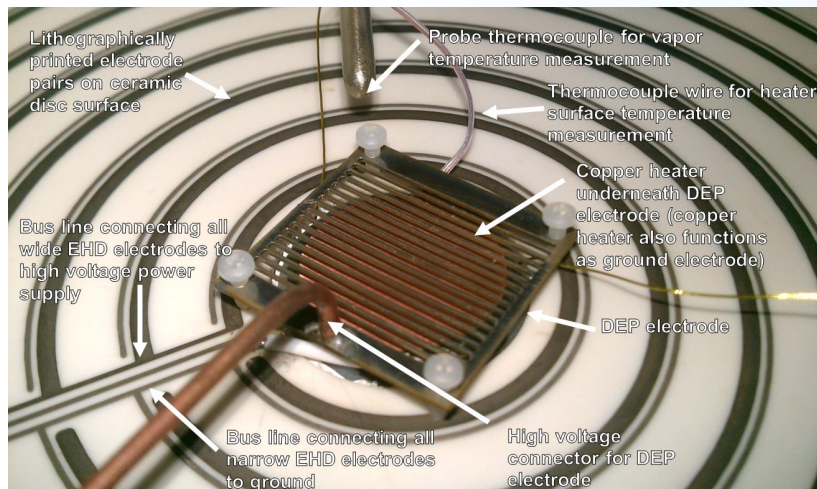


EHD Thin Film Boiling Experiment: Combined Di-electrophoretic & Conduction Pumping

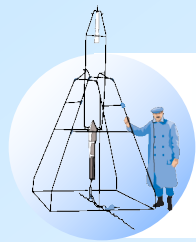
Objective:

- Investigate combined effect of Dielectrophoretic Force and Electrophoretic Force (Conduction Mechanism) on heat transfer enhancement

$$F_{DEP} = 2\pi a^3 \epsilon_1 \left(\frac{\epsilon_2 - \epsilon_1}{\epsilon_2 + 2\epsilon_1} \right) \nabla |E_e|^2$$

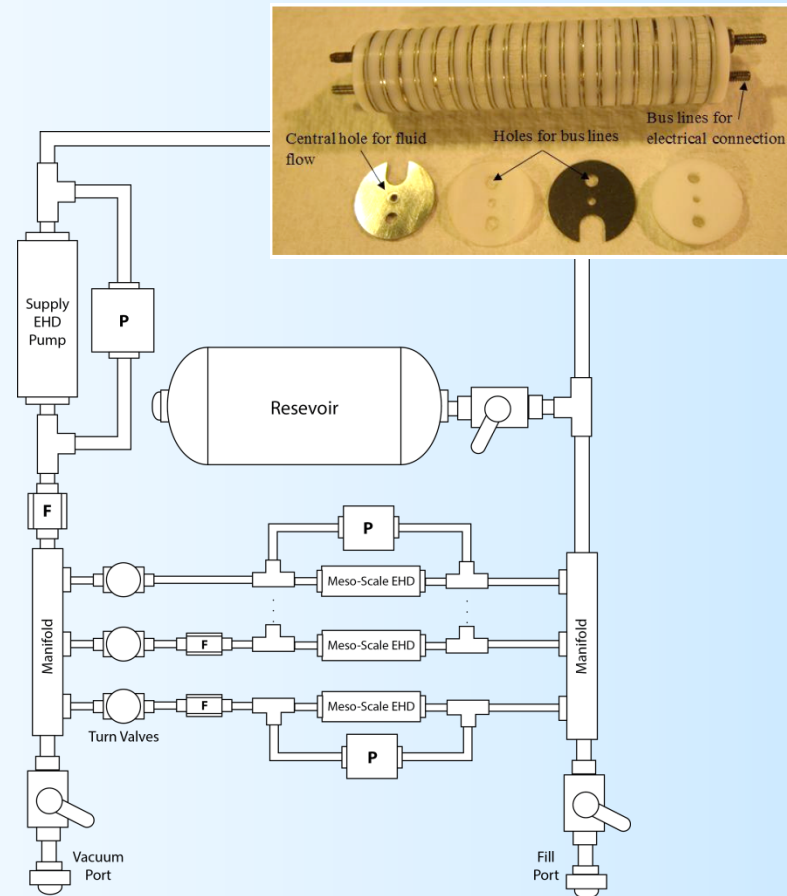


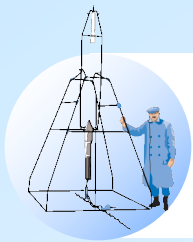
- 2 mm liq. film, 0 kV applied EHD potential, DEP electrode removed, $P_{sat}=80.0$ kPa, $T_{sat}=21.5^\circ\text{C}$
- ◇ 2 mm liq. film, 0 kV applied EHD potential, 2.5 kV applied DEP potential, $P_{sat}=78.2$ kPa, $T_{sat}=20.9^\circ\text{C}$
- 2 mm liq. film, 1.5 kV applied EHD potential, 2.5 kV applied DEP potential, $P_{sat}=78.5$ kPa, $T_{sat}=21.0^\circ\text{C}$
- ◆ 2 mm liq. film, 2.0 kV applied EHD potential, 2.5 kV applied DEP potential, $P_{sat}=78.8$ kPa, $T_{sat}=21.1^\circ\text{C}$
- ▼ 10 mm liq. pool, 0 kV applied EHD potential, 2.5 kV applied DEP potential, $P_{sat}=79.7$ kPa, $T_{sat}=21.4^\circ\text{C}$



Meso-Scale Flow Distribution (NSTRF)

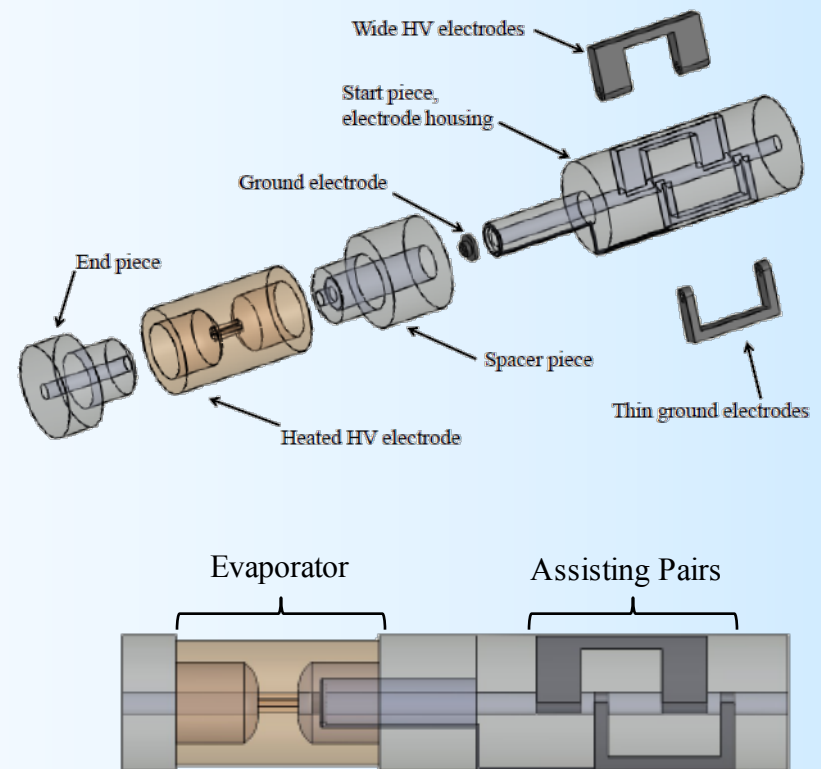
- Single and two-Phase flow
- Three parallel branches
- Entirely EHD driven
 - Branch embedded pumps
 - Flow supply pump
- Flow regime influence
- Flow distribution
 - Flow redirection
 - Maldistribution correction
 - Two-phase distribution stabilization





Micro-Scale EHD Enhanced Evaporation (NSTRF)

- Feasibility of embedded EHD enhancement
- Characterization of micro-scale perforations
 - Pressure generation
 - Flow rate generation
 - Flow regime estimate
 - Dry-out conditions
- Heat exchange loop
- Three electrode pairs
 - Two assisting upstream
 - One embedded in evaporator





NASA SPACE TECHNOLOGY RESEARCH FELLOWSHIP

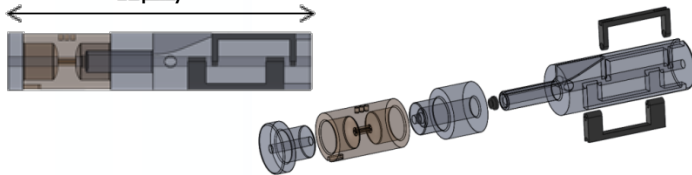
Grant NNX14AM43H

GOAL / EXPECTED OUTCOMES

- Study flow distribution control behavior utilizing Electrohydrodynamic (EHD) conduction pumps at multiple size scales
- Study the effectiveness of EHD flow distribution systems for heat transfer using single and two-phase flows at different scales
- Obtain fundamental understanding of EHD conduction flow distribution behavior at small scales and model it mathematically
- Obtain best design practices for EHD conduction driven flow distribution systems at different scales

TECHNICAL APPROACH

- Initially meso-scale EHD conduction driven flow distribution experiments for both single and two-phase flows, to be scaled down in future
- Micro-scale EHD pump embedded in an evaporator for two-phase flow enhancement options
- Mathematical modeling of the fundamental physics and chemistry at micro and nano scales
- COMSOL Multiphysics software for numerical simulations



Micro-Scale EHD Pump Design:
One Electrode Pair in Evaporator, Two Pairs Upstream

RELEVANCE TO NASA

- Research into Advanced Pumps, under the Heat Transfer and Thermal Control Systems TABS elements (14.2.2.2.3)
- EHD pumps have no moving parts, no fluid degradation, simple designs
- EHD conduction pumping is operational in zero gravity, with a TRL of 5 for the basic mechanism
- Possible usage in multi-purpose structural/thermal panels and in embedded electronics cooling for space applications

TITLE

STUDY OF MICRO/NANO SCALE EHD-DRIVEN FLOW DISTRIBUTION CONTROL & HEAT TRANSFER ENHANCEMENT FOR THERMAL CONTROL SYSTEMS

SPACE TECHNOLOGY FELLOW

Michal Talmor

FACULTY ADVISOR / PRINCIPAL INVESTIGATOR

Jamal Yagoobi

UNIVERSITY

Worcester Polytechnic Institute

DEGREE PROGRAM

Mechanical Engineering

NSTRF YEAR (e.g., 1 of 4)

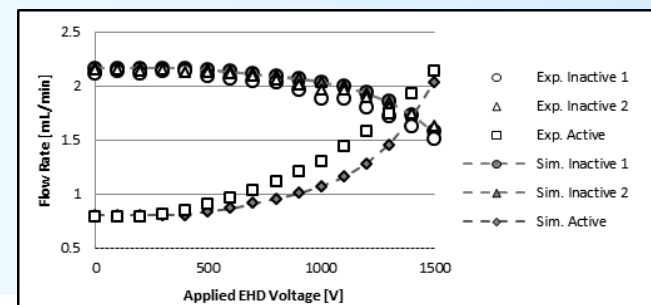
1 of 4

RESEARCH COLLABORATOR (include NASA Center or Affiliation)

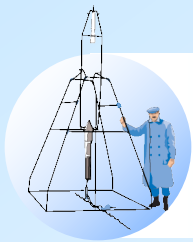
Jeffrey R. Didion
NASA Goddard Space Flight Center

MAJOR ACCOMPLISHMENTS (TO-DATE)

- Meso-scale, single phase EHD conduction driven flow distribution experiments & numerical simulations based on performance information
- Partially completed meso-scale, two-phase EHD conduction driven flow distribution experiments
- Numerical COMSOL simulation of single phase EHD conduction using the macro-scale coupled electrostatic, chemical and fluid equations
- Fundamental explanation of temperature dependence of EHD conduction pressure generation performance
- Design and partial manufacturing of a micro-scale evaporator-embedded EHD pump and experimental loop for two-phase flow
- Design draft of a CubeSat structural panel with embedded distributive flow control using EHD conduction pumps

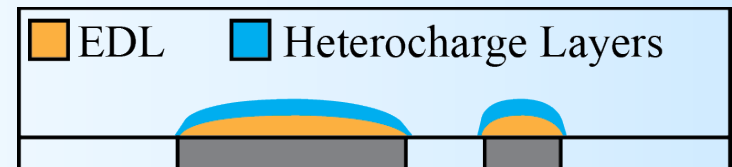


EHD Conduction Driven Maldistribution Recovery
in Single Phase, Meso-Scale Flow in Three Branches



Nano-Scale Feasibility & Numerical Study (NSTRF)

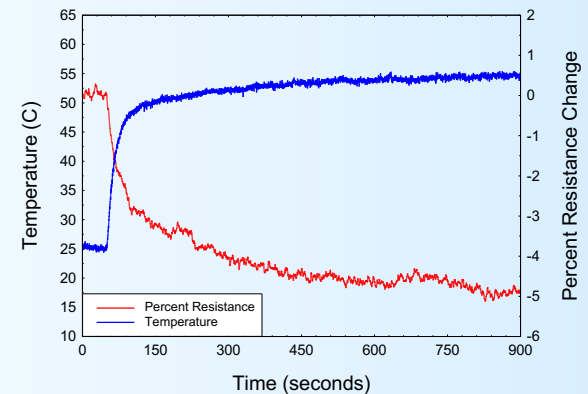
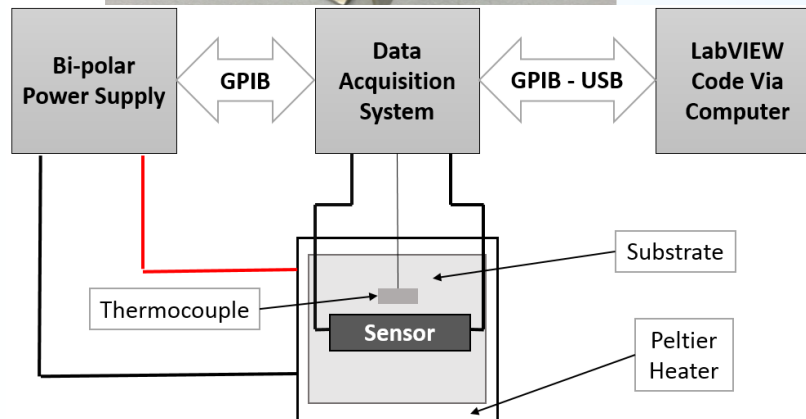
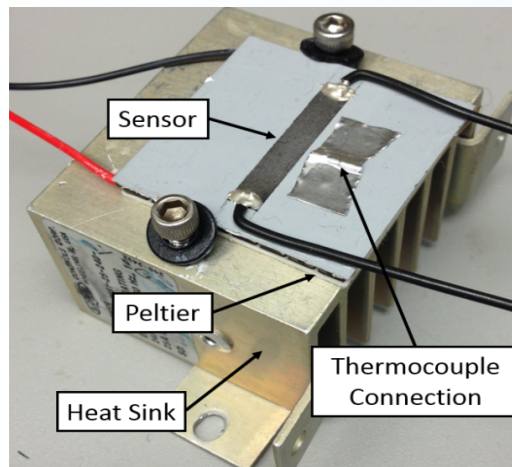
- Modeling & simulation:
 - Electric double layer vs. heterocharge layers
 - Significant effects from the zeta potential
 - Capillary and electrophoresis effects
 - Dimensions and materials revisit
- Experimentation:
 - Lithographic printing
 - Flow visualization
 - Single channel
 - Flow distribution



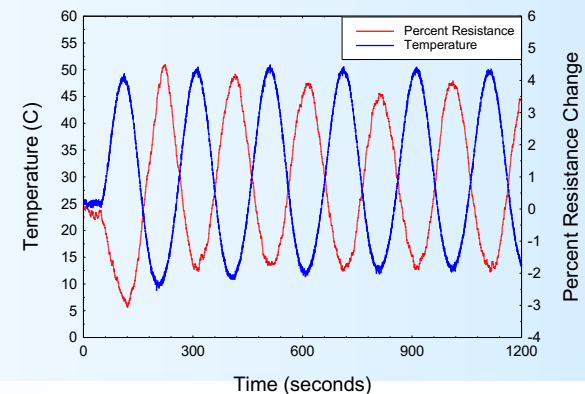


Self Sensing Thermal Management Using Nano-Enhanced Polymers

Multifunctional Nano-enhanced Structure acts as 'nervous system' to map temperature distribution

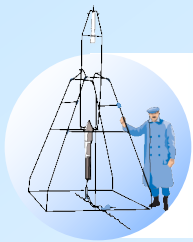


Temperature Step Function Response on Invar



5 mHz Sine Wave Response on Invar

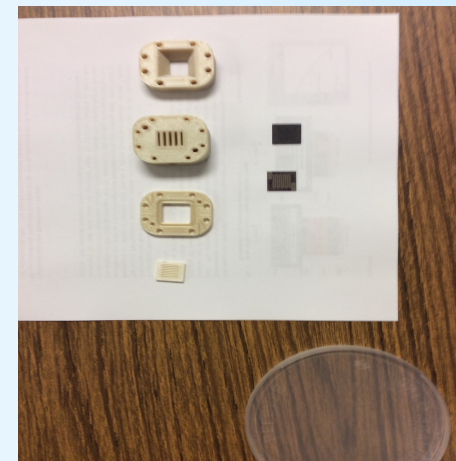




Component Heat Acquisition Proof of Concept

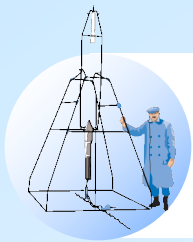
Component high heat flux embedded heat acquisition is high impact, unique technology enabling next generation of thermally limited, NASA and commercial computing, power and multifunctional platforms

- CI-TMS is innovative and unique
 - Chip Embedded Hybrid EHD/capillary device provides high heat flux acquisition at heat source
 - Thin Film Evaporation and High Heat Rejection Temperature enable SWaP-C advantages
- Spaceflight Validation of Technology Concept on CubeSat Platform



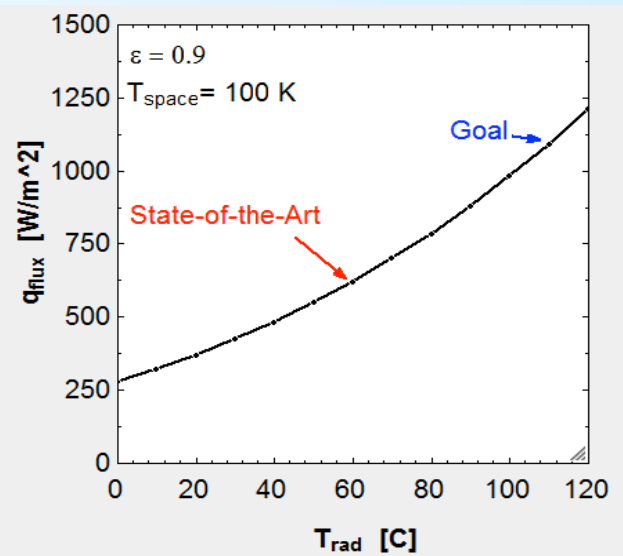
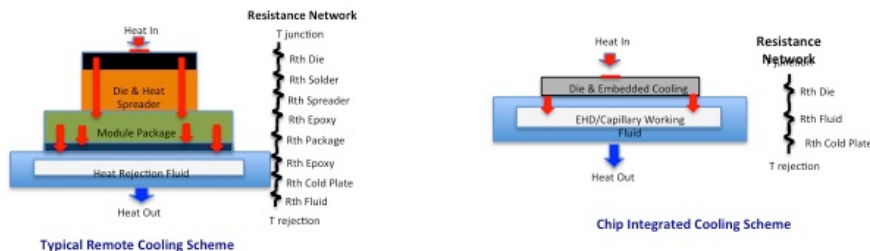
CI-TMS Proof of Concept Heat Acquisition Hardware

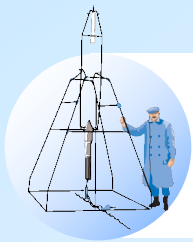




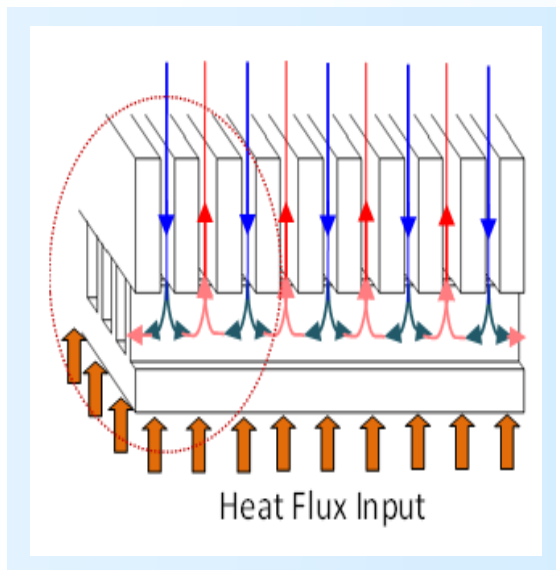
Component High Temperature Heat Acquisition Advantages

**Higher Heat Rejection Temperature
Lower System Thermal Resistance**

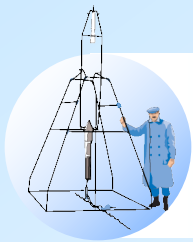




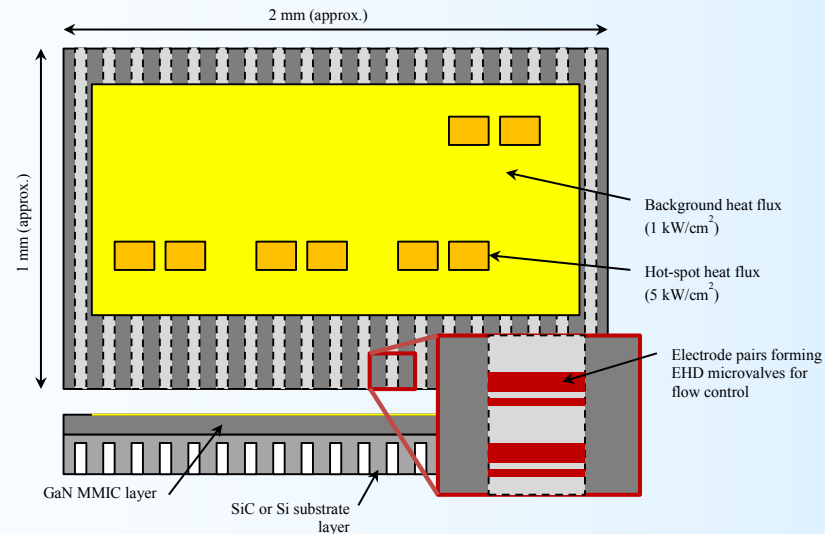
Silicon Based Concepts

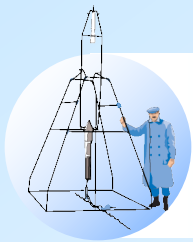


- Chip Integrated Component: High Temperature Heat Acquisition & Transport
 - Thin Film evaporation for high heat acquisition rates @ low temperature difference
 - Hybrid EHD/Capillary Fluid Management
- Silicon Manifolds Operations
 - Liquid (blue) to heat acquisition site
 - Vapor (red) transported to heat rejection site
 - Manifold channels ~ 100 microns (gravity independence & micro-scale applications)
 - Electrohydrodynamic enhanced: alleviate dry-out; insure gravity insensitivity
- Technologies to Enable the Concept
 - Capillary driven flow: self regulation of mass flow rate
 - Electrohydrodynamics (EHD): fluid management (liquid/vapor control), pump enhancement
 - DRIE to manufacture micro-channels
- Feasibility
 - Micro-scale capillary performance demonstrated
 - EHD micro-scale microgravity fluid management in micro-gravity campaigns (May 2012 & September 2013)
 - Manufactured Proof-of-Concept micro-channel EHD electrode system
 - Manufactured Capillary Proof of Concept hardware



Silicon Based Concepts: EHD Based Thermal Management of Hot Spots





Technical Overview

Electrohydrodynamic (EHD) Conduction mechanism to actively distribute fluid flow in micro-channels to local hot spots

- Technical Milestones:
 - Demonstrate Ultra High High Heat Flux Thermal Management:
 - 1 kW/cm² in background
 - 5 kW/cm² at local hot spots
 - Technically Relevant Issue
 - Commercial Applications:
 - Teledyne Scientific Corp: RF amplifiers
 - UTC: power electronics
- USAF Space Vehicles; CITMAV Consortium

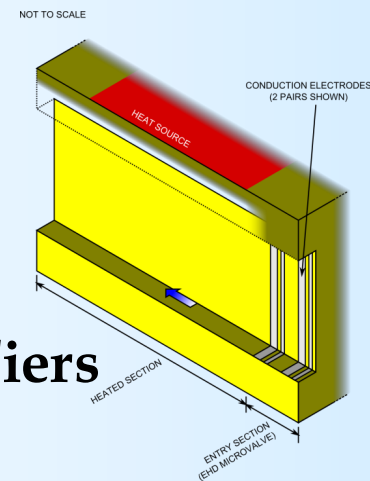
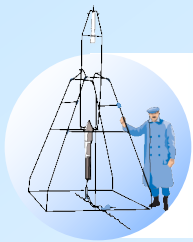
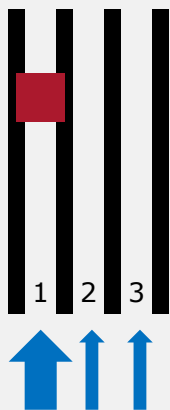


Figure 1. Simplified concept schematic showing the cross-section of a single microchannel.



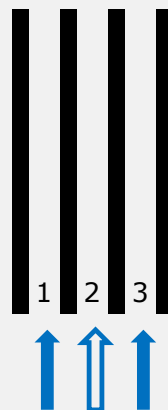
Technology Development Plan: Operational Approach

Example 1



Increase flow to
channel 1 due to
temporary hot-spot in
that region

Example 2

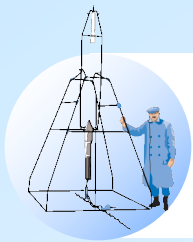


Overcome
maldistribution by
delivering
supplemental pressure
head to channel 2,
restoring flow through
that channel

Channel Pressure Drop
geometry
mass flux
heat flux

EHD Pressure Head must
be of same order as channel
Pressure drop to be effective





NASA Relevance

– NASA Space Technology Roadmaps:

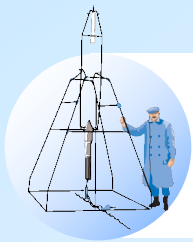
- *TA 5: Communications, Navigation, and Orbital Debris Tracking and Characterization Systems*
 - *TA 5.5.2 Power Efficient Technologies (Ka Band amplifiers)*
 - *TA 5.2.6: Antennas (Ka Band Phased Arrays)*
 - *TA 5.5: Integrated Technologies – Radio Systems (reduced SWaP)*
- *TA 14: Thermal Management Systems*
 - *TA 14.2.1: High Heat Flux Acquisition @ constant Temperature*
 - *TA14.2.2: Advanced Efficient Pump Techniques; specifically calls out EHD pumping*

– Decadal Survey Missions

High Power RF Amplifiers (HPA) have thermal challenges that limit microwave (communication and radar) performance

- *Aerosol, Cloud and Ecosystem (ACE)*
- *Snow and Cold Land Processes (SCLP)*





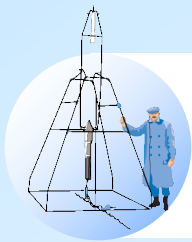
NASA Technology Point of Infusion

Integrated Radar Subsystem ACE & SCLP: Dr. Paul Racette GSFC

- *High Power Amplifiers (HPA) performance is thermally limited; Improved thermal management for GaN based amplifiers will achieve higher instrument sensitivity via higher duty cycle.*
- *Improved thermal management of high power RF signals alleviates the current frequency limitations (set by International Agreement) and enable the development of Multi-Use Systems*
 - *IIP Partnership w. Northrup Grumman to improve technical readiness for ACE Mission Integrated Radar Subsystem*
 - » *2010 IIP & 2013 IIP have identified Ka Band (35 GHz) transmit/receive module performance limitations due to thermal management*
 - *2013 IIP w. Harris Corporation identified similar thermal problems for radar technologies in SCLP hardware development*
 - *QuinStar (SBIR Phase 2) High Power Amplifier w. GaN based chips*
- *Enabling Technology: Improved transmit/receive module will permit use of synthetic aperture radars*

Dr. Racette's Group will meet with NASA/UTRC/WPI to scope issues

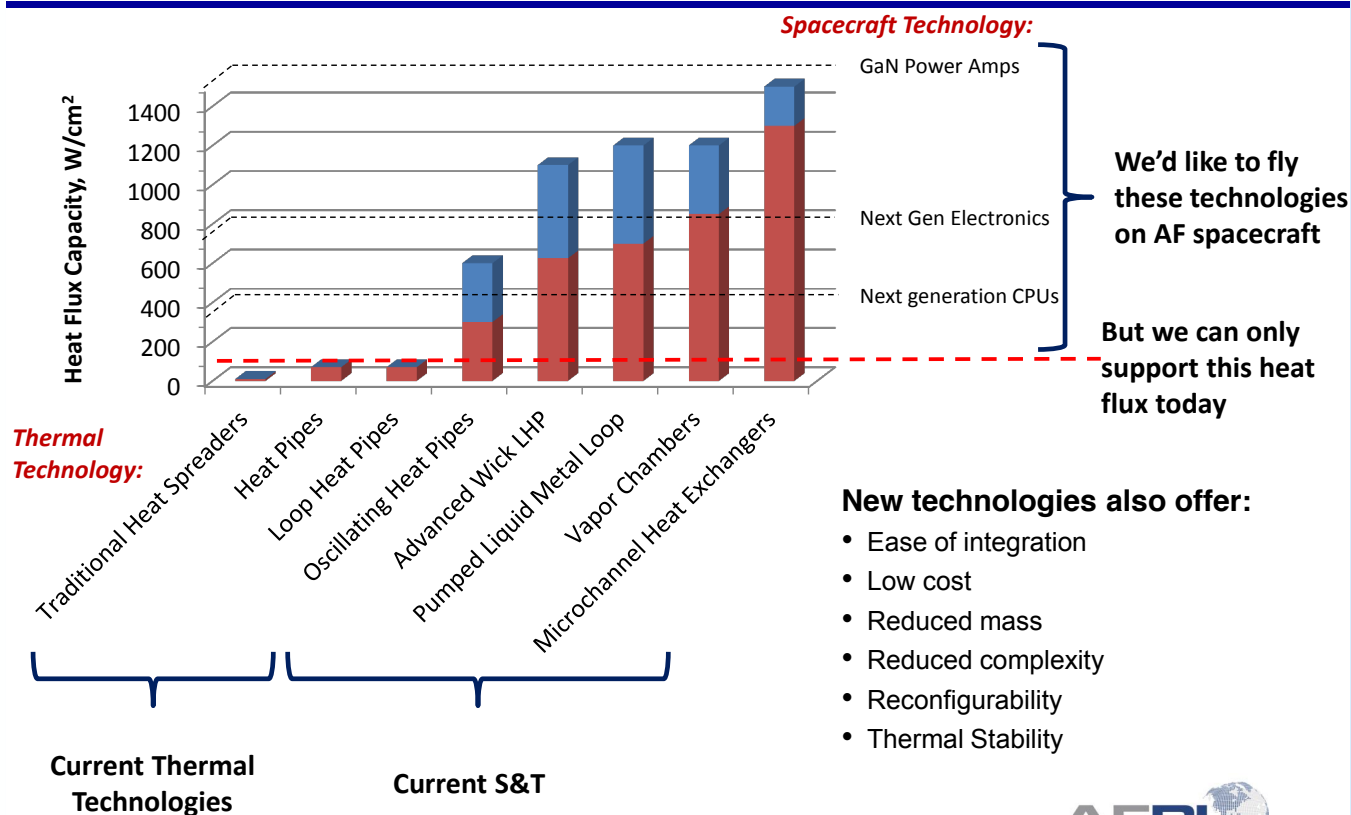




Ultra-high Heat Flux Thermal Management: Cross Agency Requirement



High Heat Flux Electronics Cooling



DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.



7



GODDARD SPACE FLIGHT CENTER

Courtesy of Andrew Williams, USAF